



Original scientific paper

Evaluating Urban Heat Island Mitigation Strategies in Rajshahi, Using ENVI-Met: A Remote Sensing Approach

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ARTICLE INFO:

Article History:

Received: 16 May 2024

Revised: 3 September 2024

Accepted: 4 September 2024

Available online: 13 September 2024

Keywords:

Urban Heat Island,
Mitigation Strategies,
Urban Micro-Climates,
Simulation,
Thermal Comfort,
Green Infrastructure,
ENVI-met Simulation.

ABSTRACT



The Urban Heat Island (UHI) effect is a critical environmental challenge in the 21st century, intensified by rapid urbanization and industrialization. This study focuses on Rajshahi, a rapidly urbanizing city in Bangladesh, where the UHI effect has already begun to manifest significantly. Utilizing ENVI-met software, a comprehensive analysis was conducted to evaluate the effectiveness of urban vegetation strategies, such as green roofs and street planting, in mitigating local temperatures and improving outdoor thermal comfort in Rajshahi's Central Business District. The findings reveal that these mitigation strategies can reduce air temperatures by up to 10 Kelvin, providing substantial cooling benefits. This research highlights the importance of integrating green infrastructure into urban planning to combat the UHI effect, enhance sustainability, and improve the overall livability of urban environments. The study offers valuable insights and practical recommendations for urban planners and policymakers, aiming to foster resilient and sustainable urban development in rapidly growing cities like Rajshahi.

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Publisher's Note:

Journal of Contemporary Urban Affairs stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

JOURNAL OF CONTEMPORARY URBAN AFFAIRS (2024), 8(2), 546–556.

<https://doi.org/10.25034/ijcua.2024.v8n2-15>

www.ijcua.com

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Highlights:

- Increasing green roof coverage will significantly reduce surface temperatures in Rajshahi's Central Business District.
- Street planting along major roads will lower air temperatures and improve outdoor thermal comfort in Rajshahi.
- The combination of green roofs and street planting will result in a greater reduction in the Urban Heat Island effect than either strategy alone.
- The extent of green infrastructure implementation will correlate with decreased energy consumption for cooling purposes in urban buildings.

Contribution to the field statement:

This manuscript provides a novel analysis of the Urban Heat Island effect by integrating socio-economic variables with thermal imaging data, offering a comprehensive understanding of UHI's impact on urban communities. The study introduces a new methodology for assessing UHI's social and economic consequences, contributing valuable insights to urban planning and sustainability literature.

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How to cite this article:

Sadat, N., Hameem, S., & Asaduzzaman, M. (2024). Evaluating Urban Heat Island Mitigation Strategies in Rajshahi, Using ENVI-Met: A Remote Sensing Approach. *Journal of Contemporary Urban Affairs*, 8(2), 546–556. <https://doi.org/10.25034/ijcua.2024.v8n2-15>

1. Introduction

The Earth's surface has experienced significant changes during the last fifty years, mostly due to human activity, with extensive urban growth emerging as a major force. Numerous alterations to the environment result from this expansion pace, which frequently matches or exceeds the increase in the population of cities. The worldwide urban area grew at an astounding pace of 168% between 2001 and 2018 (Bhuiana and Jameib, 2024), with the fastest growth rates occurring in Asia and Africa. The UN's 2011 review of world urbanization prospects predicts that this rapidly increasing trend of urbanization would push urban areas. By 2050, urban areas are predicted to house around 70% of the world's population. (Patil & Sood, 2021).

The rapid urban growth driven by human activities is transforming natural landscapes, leading to a surge in heat emissions from sources like solar radiation, power plants, vehicles, and air conditioning units. This shift results in unique microclimates within cities, characterized by varied surface types, densities, and thermal properties. Known as the Urban Heat Island (UHI) effect, this phenomenon makes urban areas significantly warmer than the adjacent rural areas. cities become hotter, air quality worsens, and the demand for energy spikes, making it harder to achieve sustainable urban living (Oke, 1982).

This situation is not different for Bangladesh, which has experienced an unheard-of increase in urbanization in recent years. With an estimated total population of 169 million (UN, 2017), and a density of 1,153 per square kilometer in 2018 (Anwar, 2020), this developing country has been undergoing rapid urbanization. According to World Bank data, the country's urban population grew from 22.5 million in 1990 to 60 million in 2019. This rapid urban expansion has led to significant environmental challenges in major cities, including a marked increase in temperatures. The loss of natural surfaces such as forests and agricultural lands, driven by diverse climatic conditions and the burgeoning population, has exacerbated these issues. Urban areas are experiencing a worsening trend of rising temperatures, leading to more frequent and extended heat spells. While natural disasters like floods have established mitigation strategies, the recognition of urban warming as a critical issue for these cities has only recently gained prominence.

While Bangladesh as a whole faces substantial environmental challenges due to rapid urbanization, the focus on Rajshahi provides a more localized understanding of these impacts. Rajshahi, a major urban center in northwest Bangladesh, has experienced significant urban growth, which has led to notable environmental transformations. This city, known for its rapid population growth and expanding urban footprint, exemplifies the urban heat island (UHI) phenomenon. In 2011 the population of Rajshahi City Corporation area was Rajshahi 448,087, but in 2018 it increased to 552,791 (Census, 2022). The built-up area of Rajshahi has been growing at a concerning rate. The built-up area of the district has increased dramatically, covering an area of around 165 km² between 1998 and 2018. Rajshahi's urban population rate stands notably higher at 32.93% compared to Bangladesh's average of 23.3%. This statistic underscores Rajshahi's substantial contribution to the overall urbanization trend in the country, where it attracts 17.83% of all migration from rural to urban areas (Asaduzzaman & Hameem, 2021). Accompanied by the 188 km² of vegetation that was lost. The loss of green spaces and the increase in impervious surfaces exacerbate these temperature differences, making Rajshahi a critical case for studying the effects of urbanization on local microclimates.

The Urban Heat Island (UHI) effect poses a significant threat to urban environments like Rajshahi, yet there remains a notable scarcity of studies detailing potential mitigation strategies and their adaptation and implementation in this specific context. Strategies like green roofs and walls, urban green spaces like parks and tree-lined streets, cool pavements and reflective surfaces, permeable pavements, compact urban planning, and energy-efficient building designs can be very effective for UHI. For example, studies have shown that green roofs and walls can cause a reduction of surface temperatures by up to 3-5°C in cities like New York and Singapore (Oberndorfer et al., 2007). Implementation of cool pavements and reflective surfaces has led to measurable reductions in surface temperatures by 1-2°C in cities like Los Angeles and Madrid (Akbari et al., 2001). These strategies underscore their practical utility in enhancing urban sustainability and resilience to climate change impacts across diverse urban environments.

This study's main goal is to explore and promote the use of specific strategies tailored for Rajshahi, focusing on green roofs and street planting. Using simulation tools like ENVI-met software, we aim to measure how these strategies can reduce the Urban Heat Island (UHI) effect and enhance outdoor comfort in Rajshahi's Central Business District. By simulating different scenarios and analyzing the results, our

research aims to offer practical insights into integrating green infrastructure into urban planning to combat heat island effects in rapidly growing cities like Rajshahi. This study adds to the existing knowledge of the practical strategies for sustainable urban development in the face of urbanization and climate challenges. It also aims to provide actionable guidance to policymakers and urban planners on how to make cities more resilient and livable as they continue to grow.

2. Methodology

This research is dedicated to investigating the Urban Heat Island (UHI) phenomenon and assessing strategies for its mitigation, utilizing simulations to predict their potential impact. The study follows a systematic approach. The selection of a study area is the initial step, acknowledging the non-universal nature of UHI. This ensures a detailed examination of the cause-and-effect dynamics and parameters within a specific context. Subsequently, an in-depth analysis of the existing UHI effect in the chosen area is conducted, employing a Geographic Information System (GIS), existing data, and records.

A simulation zone within the study area is then identified, serving as a focal point for a comprehensive investigation into UHI and the potential effectiveness of various mitigation strategies. The existing UHI setup within this simulation zone is replicated and simulated to quantify current UHI levels, establishing a baseline for subsequent analyses.

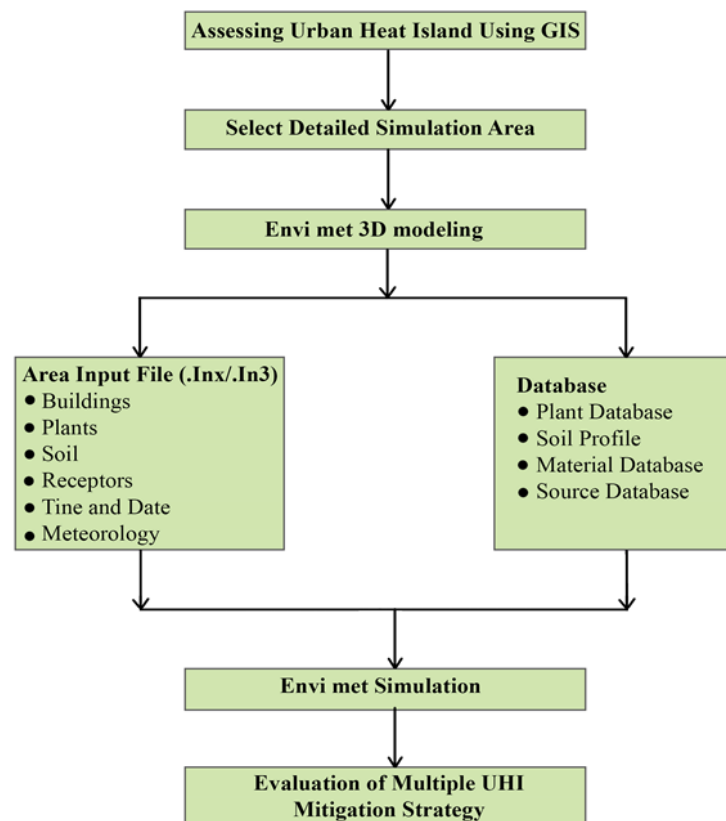


Figure 1. Structure of the Study.

Chosen UHI mitigation strategies are implemented within the simulation zone, reflecting a proactive approach to counteracting the UHI effect. The outcomes of the simulation, including temperature variations and other relevant parameters, are calculated using Envimet, providing insights into the impact of the implemented strategies. Results are meticulously compared with the prevailing UHI scenario, revealing the efficacy of selected mitigation strategies by highlighting changes in UHI levels. This systematic process contributes valuable insights into understanding, mitigating, and predicting UHI outcomes, with practical implications for urban planning and environmental management.

3. Location and Profile of the Study Area

Rajshahi has almost flat terrain, with surface elevations ranging from 1 to 18 meters. The third-largest metropolis in Bangladesh (Hameem et al., 2023), Rajshahi, is located in the northern region of the country where the number of heat-related illnesses and mortalities, and financial losses is increasing (MoHA, 2019). The district, which covers an area of around 2428 km² (Ashma et al., 2022), has a tropical wet-dry climate with an average temperature of 22°C–25°C and an annual rainfall of roughly 1448 mm. However, during summer, temperatures can soar to 42°C or even higher on the hottest days (Shahid et al., 2016). The city frequently encounters heatwaves, defined as sustained daily temperatures of 38°C or more over three consecutive days (Nissan et al., 2017). Over the past 40 years (1981–2020), temperatures between 30–36°C were most common, recorded for nearly 46% of the study period's 14,600 days. Rajshahi sees numerous days with temperatures exceeding 40°C, particularly in April and May, with the highest number of days (196) recorded in April between 38–40°C (Khatun et al., 2016). The city's heat index value reached 41, (Rajib Et.al, 2011). highlights the prominence of the Urban Heat Island (UHI) effect, significantly impacting the daily lives of its urban dwellers. Thus UHI is very prominent in Rajshahi. Also affecting the daily life of urban dwellers. Rickshaw pullers and vehicle drivers are among the most impacted, losing 20% and 18% of their incomes, respectively (Ashma et al., 2022).

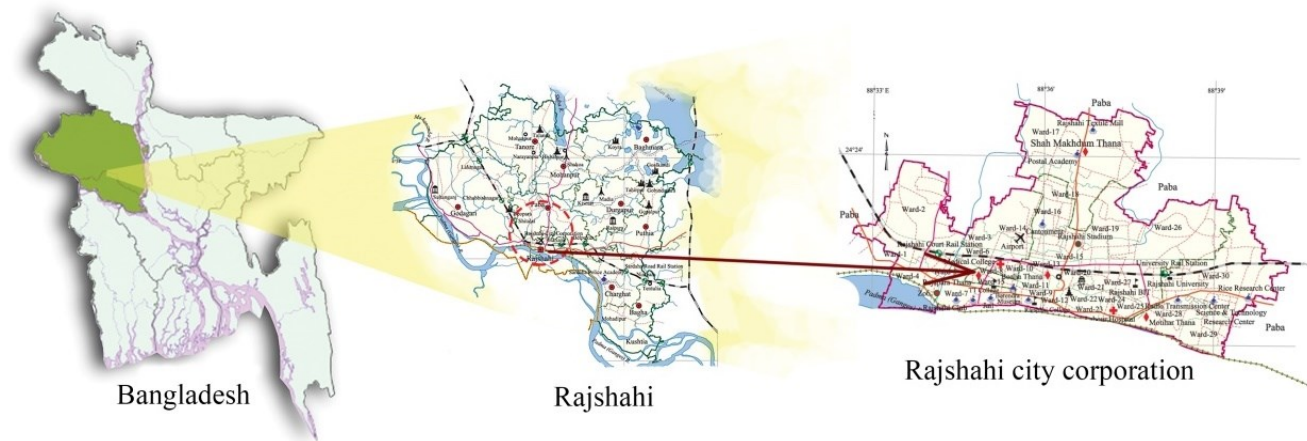


Figure 2. Location of the study area.

So, the Urban Heat Island (UHI) issue is a critical concern for Rajshahi. These reasons justify the need to study UHI in this city. Rajshahi's specific conditions make it an ideal location for UHI research within Bangladesh, setting it apart from other areas. Implementing effective mitigation strategies here could greatly reduce the suffering experienced by urban residents due to the severity of UHI effects.

4. Heat Island Effect on Rajshahi

As Rajshahi continues to develop, it is experiencing a shift towards urbanization, leading to a decline in vegetative areas and water bodies. Between 1998 and 2018, numerous water features disappeared, being replaced by either vegetation or built-up areas. The proportion of vegetated areas dropped significantly from 50.8% in 1998 to 4.03% in 2018, reflecting changes in land use and land cover (Kafy et al., 2020). This urban expansion has caused a mean temperature increase of up to 6°C in developed regions.

In 2018, large expanses of bare land that were previously water-covered in 1998 remained visible, signalling profound landscape alterations. Urban zones experienced temperatures 2°C to 4°C higher than rural areas, primarily due to reduced plant cover and an increase in impervious surfaces, which changed local thermal dynamics. Consequently, urban surface temperatures averaged 3.68°C higher than ambient air temperatures (Ashma et al., 2022). These changes underscore the critical impact of urbanization on local climates, highlighting the necessity for sustainable urban planning.

Land surface temperatures (LST) have progressively increased, ranging from 17°C to 25°C in 1998, 18°C to 33°C in 2008, and 26°C to 42°C in 2018. In 1998, 40.28% of the area had temperatures between 28°C and 30°C, which grew to 44.05% in 2008. The city centre has become increasingly susceptible to extreme heat, with an approximately 13°C rise in LST between 1997 and 2017 (Al Kafy et al., 2020). This rapid

increase in surface temperatures suggests a growing risk of amplifying the Urban Heat Island (UHI) effect. Simulated data from June 1, 2020—one of Rajshahi's hottest days—corroborated these observations, confirming a troubling trend. The escalating temperatures contribute to the UHI effect, making urban regions substantially warmer than their rural surroundings.

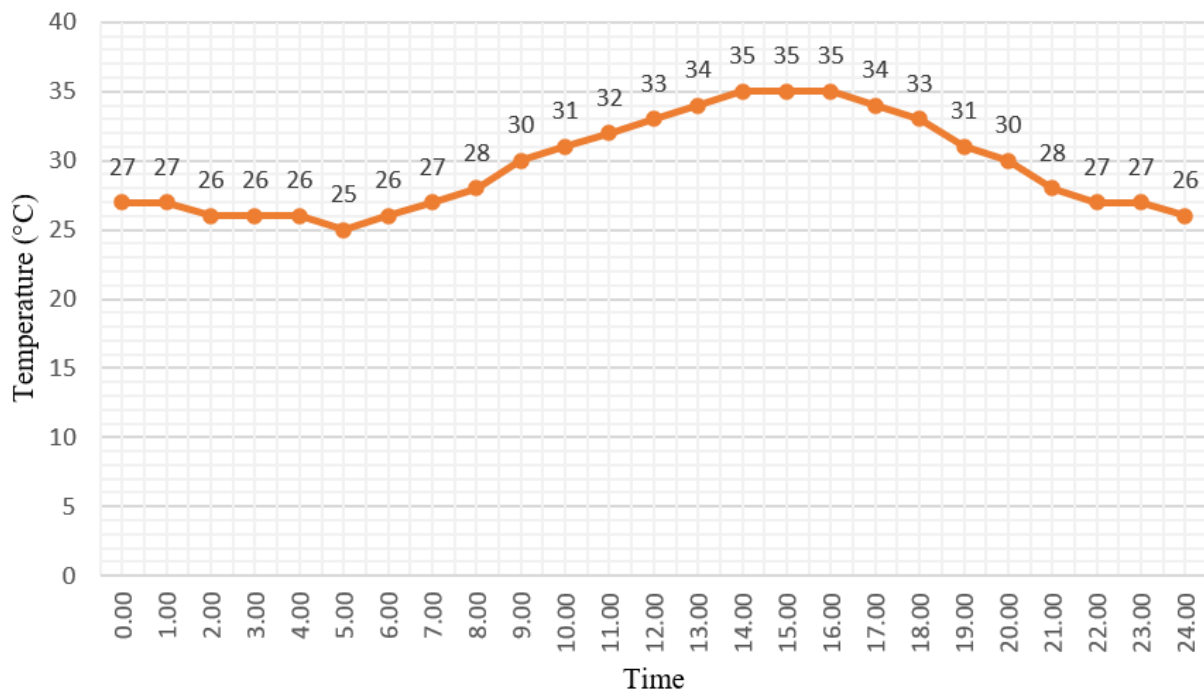


Figure 3. Simulated Hourly Weather Data on 01 June 2020.

This raises questions about the UHI's mitigating plans. However, choosing the best plans and implementing them over the entire city is an extremely time-consuming process that may not even be deemed possible. In order to minimize UHI, a more focused zone that is near the CBD region was chosen for a deeper examination. For this reason, the route that leaves the city centre and runs between the train station and the CBD was selected. Since this route serves as Rajshahi's main commercial thoroughfare, a great deal of public traffic passes through it

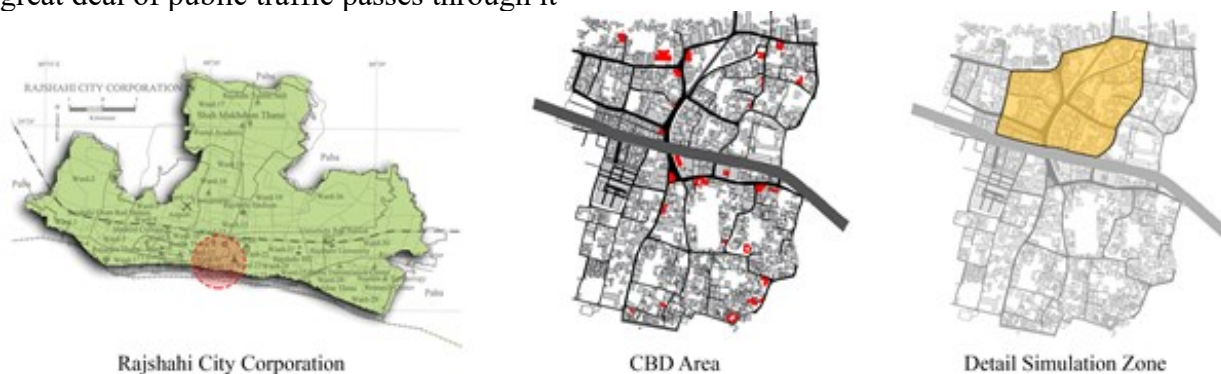


Figure 4. Detailed Simulation Zone.

Additionally, a simulation was run over the chosen zone using Envimet to view the hourly temperature data for this region. It showed that the temperature reaches its maximum point at noon (15:00) at 35°C and its lowest point at five in the morning. But the temperature stays between 30°C and 35°C throughout the whole day, and it starts to drop in the evening and stays between 25°C and 28°C. Furthermore, a temperature map was created in the designated area. Even though this simulation was carried out in June, the data is primarily within this proximity for eight to nine months out of the year because this is a major summer region where summer lasts for about three-quarters of the year.

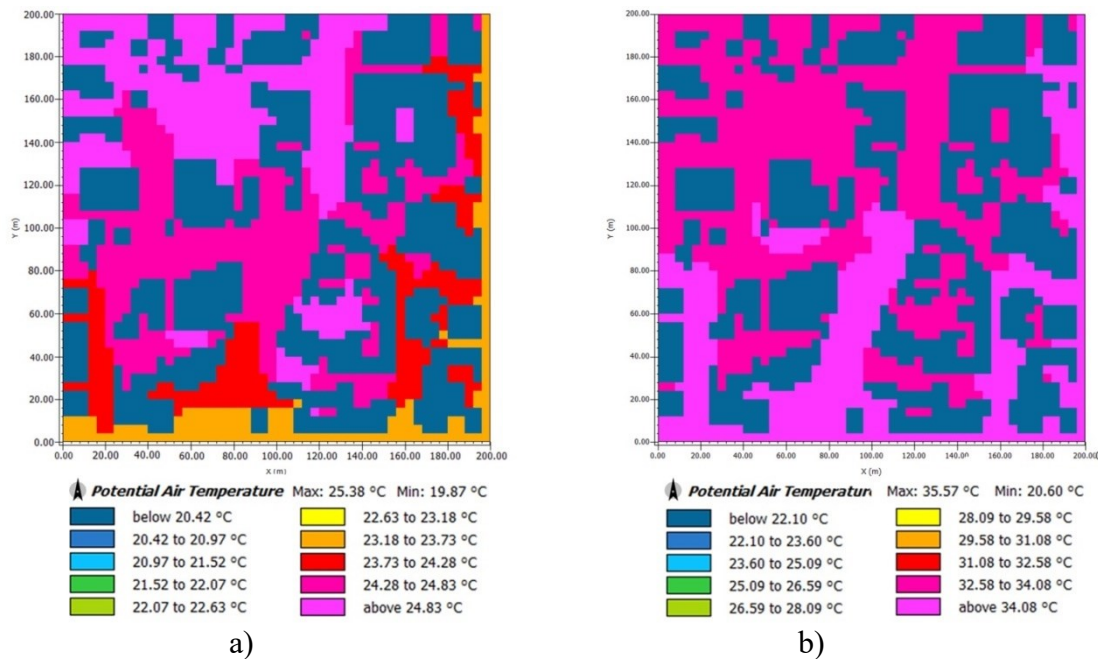


Figure 5. Potential Air Temperature 01 June 2020 a) 05:00 am. b) 15:00 pm.

5. Heat Island Effect Reduction Strategies

Strategy 01: street planting

One of the most efficient ways to mitigate the Urban Heat Island (UHI) impact is to strategically plant more street plants (Nuruzzaman, 2015), especially along the major road spine of the zone of interest. The road's breadth plus the existence of a central island or barrier between lanes create the ideal environment for adding vegetation. In order to prevent direct sunlight from damaging the road surface and to absorb a significant quantity of heat, this concept calls for the purposeful strategic planting of trees to offer shade. Street planting is positioned as a potent way to drastically lower the UHI effect in the chosen zone because of its dual use. An extensive Envimet simulation was run on the selected region in order to validate this claim and calculate the precise impact on temperature decrease. The results of the simulation showed that, as predicted, surface heat peaks during midday. Variations in daytime temperatures were between a minimum of around 19°C and a maximum of roughly 33°C. The neighbourhood is now a designated hot zone due to the traffic congestion that exacerbates the heat-related problems. This causes discomfort not just for onlookers but also for building facades, where it radiates heat and makes living conditions worse for occupants.

To determine how effective the chosen technique of expanding vegetation—in particular, street planting—was, it was put to the test through simulation. The findings showed a significant temperature variance, down to a high of 8.57 kelvin. However, in some areas, it is about 11 kelvin. This notable drop in temperature highlights the potential benefits of street planting in mitigating the urban heat island effect and enhancing overall comfort levels in the selected area. Thus, the implementation of street planting is demonstrated to be a feasible, useful, and significant approach to mitigating the problems associated with elevated temperatures in cities.

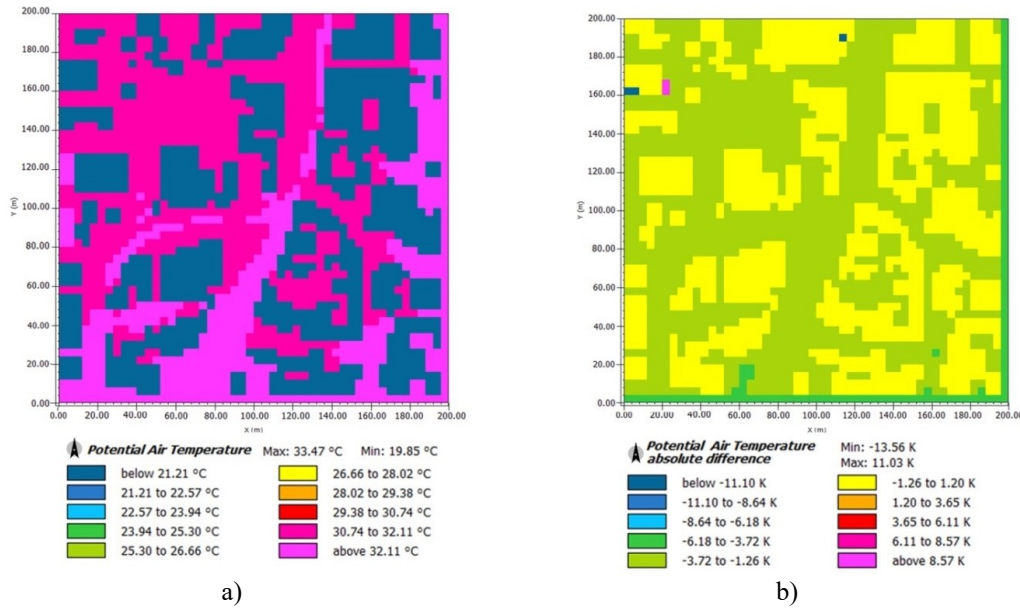


Figure 6: a) Potential Air Temperature after street Planting at 15:00 on 01 June 2020, b) Comparison of Potential Air Temperature between before and after street Planting at 15:00 on 01 June 2020.

Strategy 02: Green Roofing

Taking the fight against the Urban Heat Island (UHI) effect a step further, the emphasis is now placed on green roofing techniques on nearby rooftops and terraces as well as the hard surfaces of highways. By mitigating the effects of direct heat on structures, this supplementary measure offers a comprehensive strategy for lowering the temperature in the designated zone (Tabassum et al., 2020). The intentional growing of flora on roofs as a protective layer that lessens the effects of heat is known as "green roofing". The efficiency of the green roofing technique in lowering surface temperatures was assessed using simulations. The simulation's findings showed a significant drop in surface temperature, with a maximum drop of almost 1 kelvin. This result demonstrates how green roofing may reduce the urban heat island effect and provide a more pleasant urban environment. Furthermore, adding indoor plants to terraces improves the method for reducing heat. The results of the simulation suggest that terraces with indoor plants help to mitigate heat gain. This dual-purpose strategy adds an aesthetically beautiful and environmentally beneficial addition to metropolitan areas while also helping to lower temperatures.

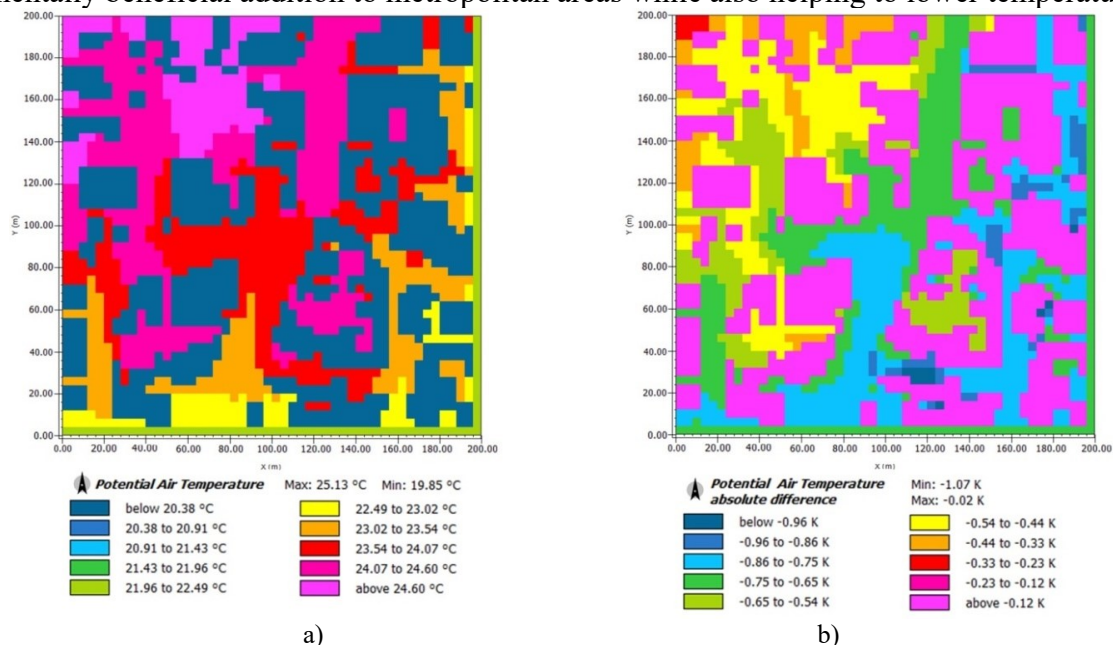


Figure 7. (a) Potential air temperature after roof greening at 15:00 on June 1, 2020, (b) Comparison of potential air temperature before and after roof greening at 15:00 on June 1, 2020.

6. Results and Discussion

In Rajshahi, strategies like green roofs and street planting are particularly advantageous for mitigating the Urban Heat Island (UHI) effect due to their cost-effectiveness and ease of implementation. Implementing green roofs expenses is relatively low compared to the long-term savings on energy bills (Berardi et al., 2014). When combined with shading or utilized alone, evapotranspiration can lower summertime peak temperatures by 1-5°C. (Kurn et al., 1994).

In the chosen zone, street planting and green roofing techniques each make a significant difference in lowering surface temperatures. In June 2020, simulations showed that when green roofing was used alone, it reduced surface temperatures by almost 1 kelvin during the day when they were at their highest. This suggests that the simulated area is having a beneficial effect on heat mitigation.

By contrast, street planting proved to be a more effective method, exhibiting a significant drop of more than 8 kelvin over the same time of day in the simulated region. Street planting worked well during the day and continued to have an effect at night. This impressive performance demonstrates how Effective Street planting is in reducing surface heat and, as a result, reducing Rajshahi's urban heat island effect.

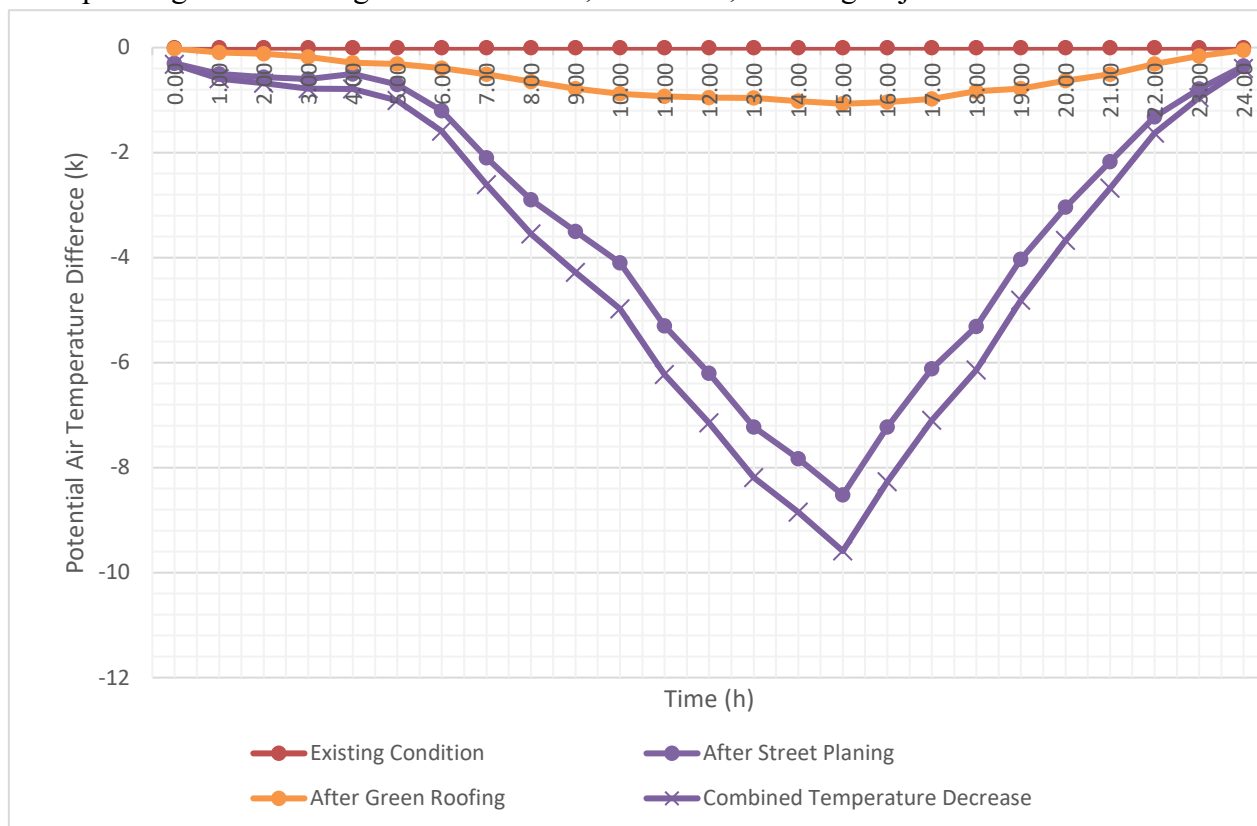


Figure 8. Comparison of the reduction in surface temperature after adopting the mitigation strategies.

Additionally, combining green roofs with street planting was found to create a synergistic effect, reducing surface temperatures more effectively than using either method alone. This complementary approach enhances heat mitigation, making Rajshahi's UHI strategy more effective. Unlike traditional methods such as reflective pavements or expanded air conditioning, which can be expensive and energy-intensive, green roofs and street planting provide a more affordable and sustainable solution.

Research on UHI mitigation in Rajshahi using green roofs and street planting is limited by its reliance on remote sensing, which may not accurately reflect local conditions. Practical challenges such as building suitability, maintenance, and water availability complicate implementation. Additionally, a lack of long-term, Rajshahi-specific data and financial constraints can hinder the effective application and adoption of these strategies.

7. Conclusions

In Rajshahi, the study demonstrates that green roofs and street planting are effective strategies for mitigating the Urban Heat Island (UHI) effect by reducing surface temperatures and enhancing urban livability. Simulations conducted using the ENVI-met software show that these strategies can lower air temperatures by up to 10 Kelvin, significantly improving outdoor thermal comfort in the city's Central Business District. This research provides critical insights into the potential of integrating green infrastructure into urban planning to mitigate UHI impacts in rapidly growing cities like Rajshahi, contributing to more sustainable and resilient urban environments.

To effectively combat the UHI effect in Rajshahi, it is essential to expand the implementation of green roofs and street planting throughout the city. Increasing the number of green roofs can substantially lower building temperatures, reduce energy costs, and improve overall urban climate resilience. This approach should be incentivized through subsidies, tax benefits, and policy measures that encourage property owners to adopt green roofing practices. Additionally, expanding street planting along major roads and public spaces, with a focus on native and drought-resistant tree species, can offer a sustainable solution for temperature regulation and urban cooling.

Successful UHI mitigation in Rajshahi requires an integrated approach that involves both green roofs and street planting within the broader framework of urban planning. Policymakers should consider launching pilot projects on public buildings and strategic urban locations to demonstrate the effectiveness of these strategies, thereby fostering wider community adoption. Collaboration with local stakeholders, community education campaigns, and partnerships with environmental organizations will be vital in tailoring these mitigation measures to the city's specific needs and ensuring broad public support and participation.

Future research should focus on assessing the long-term effectiveness of these UHI mitigation strategies under varying climatic conditions in Rajshahi. Additionally, investigating innovative materials, smart technologies for cooling and irrigation, and evaluating the socio-economic impacts, such as energy savings and public health benefits, can further enhance the effectiveness of these strategies. These insights will support the continuous improvement and expansion of UHI mitigation practices, making Rajshahi more resilient to climate change and promoting sustainable urban development.

Acknowledgements

The authors extend their gratitude to the Bangladesh Bureau of Statistics (BBS) for providing the existing dataset that was instrumental in this research.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of Interest

The author(s) declare(s) no conflicts of interest.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Institutional Review Board Statement

Not applicable.

CRedit author statement:

Nafis Sadat was responsible for conceptualization, methodology, visualization, funding acquisition, and writing the original draft of the manuscript. Sheikh Hameem managed data curation, conducted formal analysis, performed investigations, and developed the necessary software tools. Md. Asaduzzaman oversaw project administration, provided resources, supervised the research process, validated the findings, and contributed to writing, reviewing, and editing the manuscript. All authors have reviewed and approved the final version of the manuscript.

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How to cite this article:

- Sadat, N., Hameem, S., & Asaduzzaman, M. (2024). Evaluating Urban Heat Island Mitigation Strategies in Rajshahi, Using ENVI-Met: A Remote Sensing Approach. *Journal of Contemporary Urban Affairs*, 8(2), 546–556. <https://doi.org/10.25034/ijcua.2024.v8n2-15>